

The effect of geomagnetic-storm-induced enhancements to ionospheric emissions on the interpretation of the TIMED/GUVI O/N₂ ratio

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[1] We examine the consequence of enhanced atomic oxygen (OI) 135.6 nm emissions due to the recombination of O⁺ with electrons on the column number density ratio of atomic oxygen to molecular nitrogen (O/N₂ ratio) provided by Global Ultraviolet Imager (GUVI) on board the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics satellite. GUVI O/N₂ ratio is derived from the measurements of OI 135.6 nm and N₂ Lyman-Birge-Hopfield airglow emissions. The OI 135.6 nm emission arises from two sources: photoelectron impact excitation of neutral atomic oxygen and the radiative recombination of O⁺ with electrons. We estimate the O/N₂ ratio disturbance associated with the O⁺ density enhancement during geomagnetic storms through the case study of the storms on 20 November 2003 and 8 November 2004. The OI 135.6 nm emission enhancement originating from the ionosphere is derived using the Utah State University Global Assimilation of Ionospheric Measurements model ionosphere. Our results show that the O/N₂ ratio increase from the equator to middle latitudes during the storm periods is primarily associated with thermospheric neutral composition disturbances. However, the contribution of the OI 135.6 nm emission originating from the ionosphere to the storm time O/N₂ ratio increase is substantial in the northern low-middle latitude regions where severe plasma density enhancements occur during the main phase of the storms. Therefore, the ionospheric contribution should be considered for an accurate assessment of the storm time O/N₂ ratio increase at low-middle latitudes during these large storm events.

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1. Introduction

[2] The column number density ratio of atomic oxygen to molecular nitrogen (O/N₂ ratio) has been widely used as a parameter describing thermospheric neutral composition change and its effect on the ionosphere. The O/N₂ ratio has mainly been driven from optical measurements of thermospheric far ultraviolet (FUV) emissions. The Global Ultraviolet Imager (GUVI) on board the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite has been providing the O/N₂ ratio data since 2002. The GUVI O/N₂ ratio is derived from the ratio of two spectral regions: one is primarily made up of atomic oxygen (OI) 135.6 nm

emissions (there is some underlying contribution from a weak N₂ Lyman-Birge-Hopfield (LBH) band that is accounted for in the algorithm) and the other due to N₂ LBH emissions from about 140 nm to about 160 nm (termed “Lyman-Birge-Hopfield short” (LBHS)) [Paxton *et al.*, 1999, 2004; Strickland *et al.*, 1995, 2004a, 2004b; Zhang *et al.*, 2004]. The retrieval of O/N₂ ratio from dayglow observations is based on the assumption that the OI 135.6 nm emission is primarily from photoelectron impact excitation of atomic oxygen (hereafter $A_{135.6}$). However, the OI 135.6 nm emission resulting from radiative recombination of the oxygen ion (hereafter $I_{135.6}$) should not be ignored in the equatorial ionization anomaly (EIA) region [Kil *et al.*, 2013].

[3] Kil and Paxton [2011] first noticed the fact that the contribution of $I_{135.6}$ to the GUVI O/N₂ ratio is not ignorable at the EIA. Kil *et al.* [2013] estimated that 5–10% of longitudinal and latitudinal variations of the O/N₂ ratio in low latitudes are caused by the variation of the EIA intensity. Those studies investigated the $I_{135.6}$ effect on the O/N₂ ratio during magnetically quiet periods, but the contribution of $I_{135.6}$ to the O/N₂ ratio during geomagnetic storms has not yet been investigated. The ionospheric contribution to the O/N₂ ratio is expected to be more significant during geomagnetic storms, especially severe ones, than during magnetically quiet periods.

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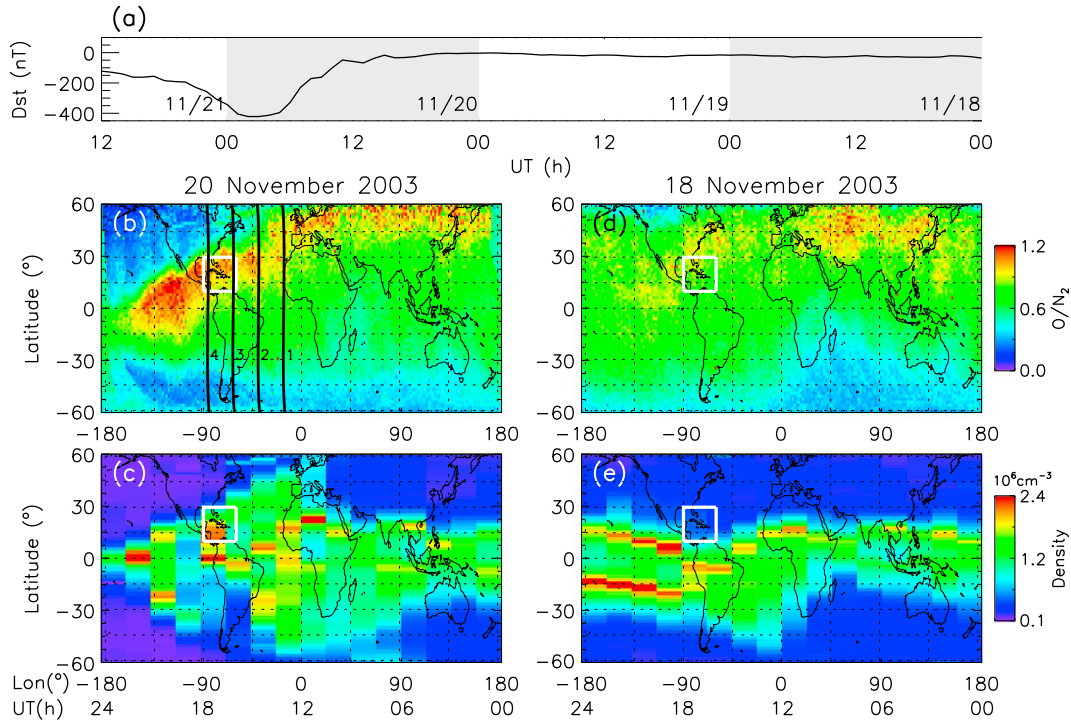


Figure 1. Observations during the 20 November 2003 storm. (a) *Dst* index. (b and c) GUVI O/N₂ ratio and CHAMP electron density on the twentieth. The vertical lines show the CHAMP orbits on the twentieth. (d and e) GUVI O/N₂ ratio and CHAMP electron density on the eighteenth. The LTs of GUVI and CHAMP observations are near 1200 and 1100 LT, respectively.

[4] We investigate the contribution of $I_{135.6}$ to the GUVI O/N₂ ratio during the large geomagnetic storms of 20 November 2003 and 8 November 2004. Our investigation focuses on the regions where both the O/N₂ ratio and the plasma density are enhanced. $I_{135.6}$ is calculated using the electron density profiles provided by the Utah State University-Global Assimilation of Ionospheric Measurements (USU-GAIM) model. The USU-GAIM model ionosphere is used after scaling with the measurements of the ion density by the Challenging Minisatellite Payload (CHAMP) satellite.

2. Data and Model Description

[5] The TIMED satellite was launched in December 2001 at an altitude of 625 km with an inclination of 74.1°. By using the cross-track scanning spectrometer design, TIMED/GUVI observes FUV airglow across the Earth's limb and disk in five spectral channels: HI 121.6 nm, OI 130.4 nm, OI 135.6 nm, N₂ LBHS (141.0–152.8 nm), and N₂ LBH long (167.2–181.2 nm) [Christensen *et al.*, 2003; Paxton *et al.*, 1999, 2004; Strickland *et al.*, 2004a]. The GUVI O/N₂ ratio is derived from the ratio of OI 135.6 nm and LBHS radiances. The observed radiances, of course, represent the integration of the product of the volume emission rate and the transmission to the observer throughout the column line of sight. This integrated quantity is well correlated and closely related to the ratio of the column content of atomic oxygen and molecular nitrogen as long as the source of the emission is photoelectron impact excitation. The “O/N₂ ratio” is referenced to the point where an integrated vertical column density of N₂ of 10^{17} cm² is reached [Strickland *et al.*, 1995; Zhang *et al.*, 2004].

[6] The CHAMP satellite was launched on 15 July 2000 into a near polar orbit at initial altitude of 454 km. The orbital inclination was 87°. The altitudes of the CHAMP satellite in 2003 and 2004 were near 400 km. CHAMP Planar Langmuir Probe (PLP) provides plasma density measurements at the satellite altitude, and the PLP data are available every 15 s.

[7] The USU-GAIM model, in particular, the Gauss-Markov Kalman Filter (GMKF) version from the Community Coordinated Modeling Center (CCMC) in National Aeronautics and Space Administration (NASA), was used in this analysis. GAIM GMKF is a physics-based data assimilation model of the ionosphere using a Kalman filter as a basis for assimilating different kinds of data. GAIM GMKF was developed at Utah State University as part of a United States Department of Defense Multidisciplinary University Research Initiative program [Schunk *et al.*, 2004]. CCMC provides three-dimensional electron density distributions at user specified times by assimilating total electron content data collected from about 200 ground stations in Global Positioning System (GPS) network into the USU-GAIM model. We calculate the OI 135.6 nm emission produced by the ionosphere using electron density profiles from USU-GAIM model after scaling them with CHAMP electron density observations.

3. Results and Discussion

3.1. 20 November 2003 Storm

[8] The GUVI O/N₂ ratio and CHAMP electron densities on 20 November 2003 (storm time) are shown in Figures 1b and 1c, and those on 18 November 2003 (quiet time) are shown in

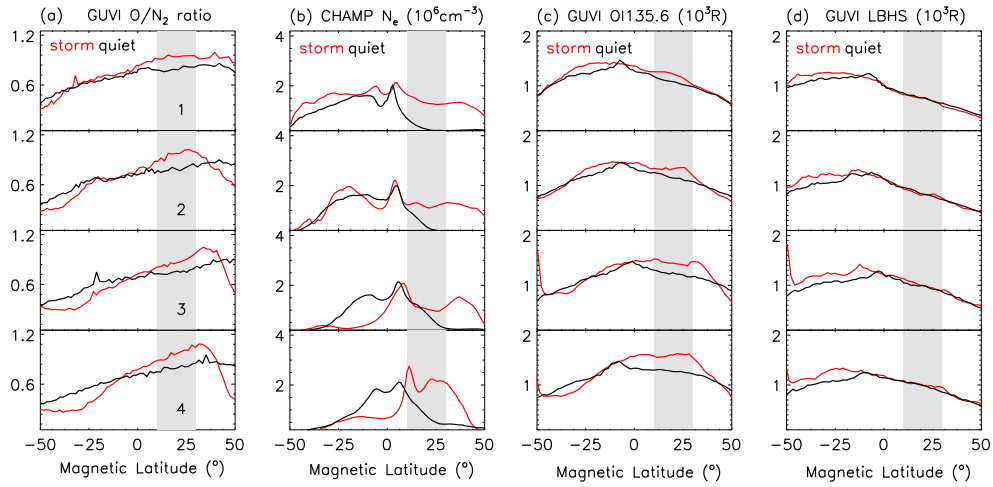


Figure 2. Comparison of the observations on 20 (red curves) and 18 (black curves) November 2003 along the CHAMP orbits shown in Figure 1b. (a) GUVI O/N₂ ratio. (b) CHAMP electron density. (c) GUVI OI 135.6 nm intensity. (d) GUVI LBHS intensity. The gray shaded regions indicate the regions where the GUVI O/N₂ ratio, GUVI OI 135.6 nm intensity, and CHAMP electron density are enhanced during the storm period, although the change of the LBHS intensity is minor.

Figures 1d and 1e. The *Dst* index is shown in Figure 1a. The vertical lines in Figure 1b indicate the CHAMP passes on the twentieth. Time progresses to the left following the TIMED and CHAMP satellite orbits. The sampling local times (LT) of GUVI and CHAMP are near 1200 and 1100 LT, respectively. The reference day for the quiet time is chosen on 18 November because the CHAMP orbits on the eighteenth closely match those on the twentieth. The CHAMP data are shown for the eighteenth and the twentieth in Figure 2.

[9] Significant changes in the O/N₂ ratio and electron density start to appear around 1200 UT on the twentieth. Compared with the O/N₂ ratio map on the eighteenth, the O/N₂ ratio reduction appears in the Western Pacific and American sectors on the twentieth in the middle- to high-latitude regions. This thermospheric neutral composition change is considered to be responsible for the storm time electron density reduction in those sectors [e.g., Kil *et al.*, 2011]. The enhancements in O/N₂ ratio appear in the equatorial region in the Western Pacific sector (140°–80°W) and in the northern low-middle latitudes in the American-Atlantic sector (80°W–0°) during the storm. In the Western Pacific sector, the electron density during the storm period is reduced compared with that before the storm. However, the electron density in the northern low-middle latitudes in the American-Atlantic sector is increased during the storm period compared with that before the storm. The storm time electron density enhancements in the northern low-middle latitudes in the American-Atlantic sector are attributed to the effects of electric fields and equatorward winds [Crowley *et al.*, 2006; Kil *et al.*, 2011; Lu *et al.*, 2008]. Neutral composition change (O/N₂ ratio increase) also contributes to the storm time electron density enhancement, but the effects of electric fields and neutral winds overwhelm the effect of neutral composition during severe geomagnetic storms.

[10] The storm time enhancements (the bright red area, in particular) of the O/N₂ ratio in the equatorial region in the Western Pacific sector are not associated with the ionosphere because the electron density in that region is reduced during the storm period; the reduction of the electron density

indicates the recombination is not contributing extra photons to the observed OI 135.6 nm intensity. Our investigation focuses on the northern low latitudes and midlatitudes in the American-Atlantic sector where there is a significant enhancement in the ionospheric O⁺. By distinguishing *I*_{135.6} and *A*_{135.6} from the GUVI OI 135.6 nm intensity data, we determine to what extent the calculated O/N₂ ratio enhancement can be attributed to the ionospheric emission.

[11] Figure 2 presents the (a) GUVI O/N₂ ratio, (b) CHAMP electron density, (c) GUVI 135.6 nm intensity, and (d) GUVI LBHS intensity along the four CHAMP orbits shown in Figure 1b. The black and red curves are the observations on the eighteenth and twentieth, respectively. Because the CHAMP orbits on the eighteenth and twentieth closely match, only the orbits on the twentieth are shown on the map in Figure 1b. The latitude interval shaded gray is the region where both the O/N₂ ratio and electron density during the storm period are greater than those before the storm. In that latitude interval, the OI 135.6 nm intensity increases during the storm period, whereas, the change of the LBHS intensity is minor. Therefore, the enhancement of the OI 135.6 nm intensity is responsible for the storm time enhancement of the reported O/N₂ ratio in that region.

[12] Using the altitude profiles of OI 135.6 nm intensity provided by GUVI limb scan, we can infer the ionospheric and thermospheric portions in the OI 135.6 nm intensity enhancements during the storm. The LT of the limb scan is about 1.5 h behind the disk scan. In Figure 3, the limb profiles of the OI 135.6 nm intensity during the quiet and storm periods are shown with black and red curves, respectively. The profiles are obtained using the data within the white boxes in Figures 1b and 1d where the enhancements in electron density and O/N₂ ratio are significant. The solid dots are the average intensities at a given height, and the horizontal bars are the standard deviations. The percentage changes of the intensity with respect to the intensity at quiet time are shown with a green curve. The percentage change increases with an increase of altitude. A significant portion of the

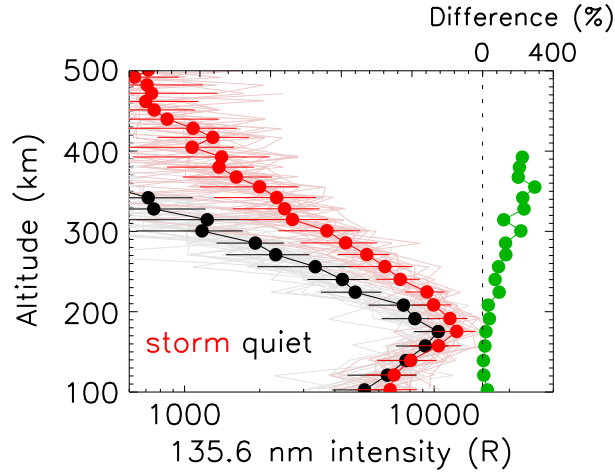


Figure 3. Altitude profiles of the OI 135.6 nm intensity derived from the GUVI limb scan data during the 20 November 2003 storm. The observations during the quiet and storm periods are shown with back and red curves, respectively. The solid dots represent the average intensities and the horizontal bars are the standard deviations. The percentage changes with respect to the quiet time intensity are shown with a green curve.

emission increase in the *F* region height (above an altitude of ~250 km) is attributed to the emission originated from the ionosphere, and therefore, the ionospheric contribution to the O/N₂ ratio increase is not ignorable.

[13] $I_{135.6}$ is calculated using the method introduced by Kil *et al.* [2013]. Here we provide a brief description of the method. Assuming that the oxygen ion is the dominant ion species in the *F* region, $I_{135.6}$ up to the satellite altitude h in Rayleigh (*R*) unit is given by the following:

$$I_{135.6}(z) = 10^{-6} \int_0^h \alpha(z) n_e^2(z) dz \quad (1)$$

[14] Here α is the radiative recombination rate coefficient of the oxygen ion, and n_e is the electron density. Both parameters are a function of the height z . We use the USU-GAIM electron density profiles scaled with the CHAMP electron density for the calculation of $I_{135.6}$. The coefficient α is expressed as a function of height and electron temperature, T_e . Because the temperature variation with height is small in the *F* region, we adopt the simple form of α given by Meléndez-Alvira *et al.* [1999]:

$$\alpha = 7.3 \times 10^{-12} \times \left(\frac{250}{T_e} \right)^{0.7} [\text{cm}^3 \text{s}^{-1}] \quad (2)$$

[15] The difference of the GUVI O/N₂ ratio between storm and quiet times ($[\Delta\text{O}/\text{N}_2]_T$) is the total change of the O/N₂ ratio and is expressed as follows:

$$[\Delta\text{O}/\text{N}_2]_T = [\Delta\text{O}/\text{N}_2]_A + [\Delta\text{O}/\text{N}_2]_I \quad (3)$$

[16] $[\Delta\text{O}/\text{N}_2]_A$ and $[\Delta\text{O}/\text{N}_2]_I$ are the changes of the O/N₂ ratio caused by the changes of $A_{135.6}$ and $I_{135.6}$, respectively.

In the regions where the change of the LBHS intensity is small (gray regions in Figure 2), the relative contribution of $A_{135.6}$ and $I_{135.6}$ to $[\Delta\text{O}/\text{N}_2]_T$ is proportional to the changes of $A_{135.6}$ and $I_{135.6}$. That is,

$$[\Delta\text{O}/\text{N}_2]_A = [\Delta\text{O}/\text{N}_2]_T \cdot \Delta A_{135.6} / (\Delta I_{135.6} + \Delta A_{135.6}) \quad (4)$$

and

$$[\Delta\text{O}/\text{N}_2]_I = [\Delta\text{O}/\text{N}_2]_T \cdot \Delta I_{135.6} / (\Delta I_{135.6} + \Delta A_{135.6}) \quad (5)$$

[17] Here $\Delta A_{135.6}$ and $\Delta I_{135.6}$ are the storm time and quiet time differences of $A_{135.6}$ and $I_{135.6}$. $[\Delta\text{O}/\text{N}_2]_T$ is directly obtained from the GUVI observations, and $\Delta I_{135.6}$ is obtained using the model ionosphere. The values of $A_{135.6}$ during and before the storm are given by the differences of the GUVI measurements of the OI 135.6 nm intensity and $I_{135.6}$. For the calculation of $I_{135.6}$, we assumed the electron temperature to be 1800 K.

[18] The average $[\Delta\text{O}/\text{N}_2]_T$, $[\Delta\text{O}/\text{N}_2]_A$, and $[\Delta\text{O}/\text{N}_2]_I$ values on each CHAMP orbit are shown in Figure 4a with black, green, and red dots, respectively. The average values are calculated using the data within the latitude interval indicated by the gray shading in Figure 2. Figure 4b shows the percentage contributions of $A_{135.6}$ and the $I_{135.6}$ disturbances to $[\Delta\text{O}/\text{N}_2]_T$. The vertical bars are the standard deviations. The O/N₂ ratio increase caused by the increase of $I_{135.6}$ is less than 20% except for the case of orbit 1. Therefore, the O/N₂

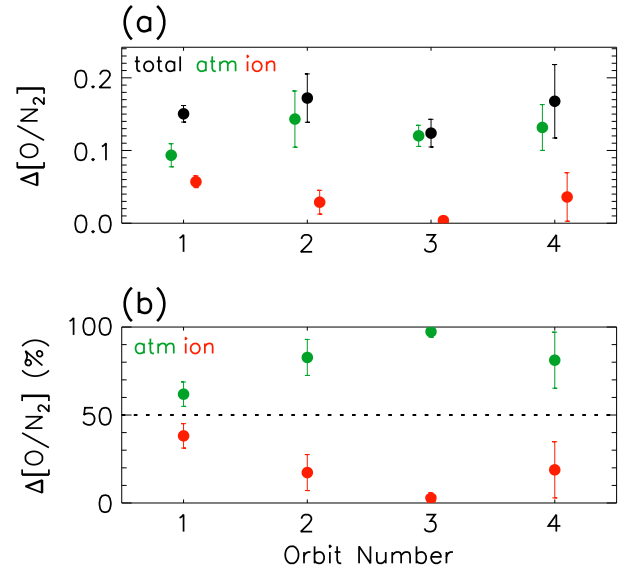


Figure 4. Comparison of the thermospheric and ionospheric contributions to the O/N₂ ratio increase during the 20 November 2003 storm. (a) The storm time increase of the O/N₂ ratio observed by GUVI (black dots) and caused by the increase of the OI 135.6 nm emission originating from the thermosphere (green dots), and ionosphere (red dots). The solid dots are the average values obtained in the gray shaded regions in Figure 2. Vertical bars show the standard deviations. (b) Percentage contributions of the OI 135.6 nm emissions originating from the thermosphere (green dots) and ionosphere (red dots) to the storm time O/N₂ ratio increase.

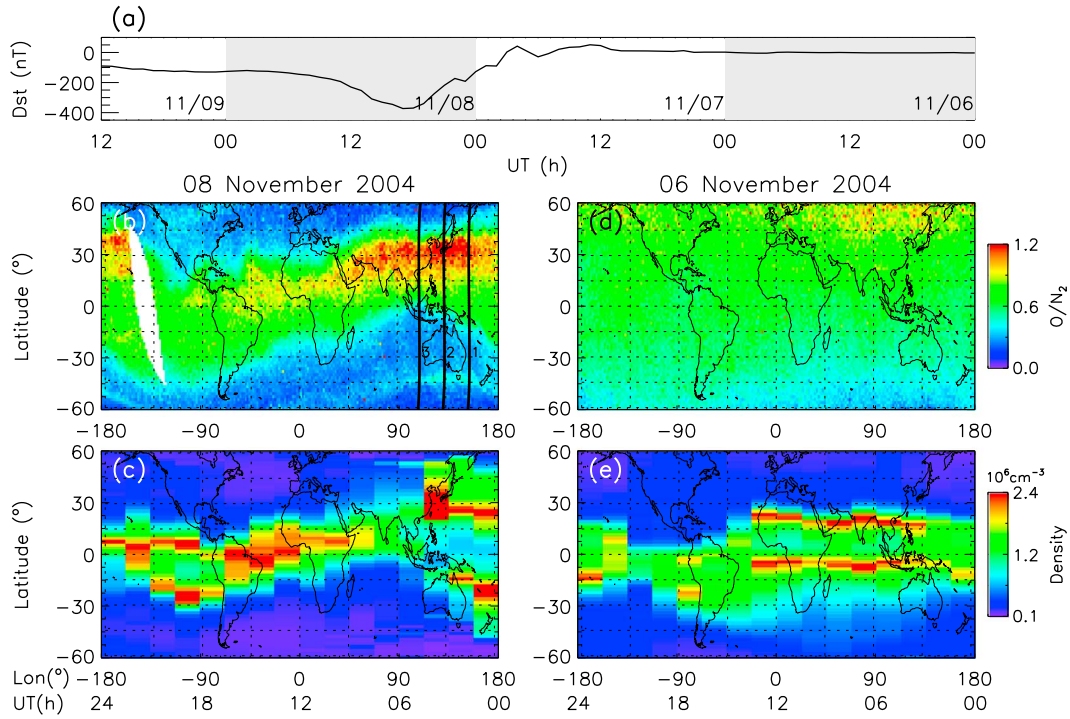


Figure 5. Observations during the 8 November 2004 storm. (a) *Dst* index. (b and c) GUVI O/N₂ ratio and CHAMP electron density on the eighth. The vertical lines show the CHAMP orbits on the eighth. (d and e) GUVI O/N₂ ratio and CHAMP electron density on the sixth. The LT of GUVI and CHAMP observations is around 1300 LT.

ratio increase during the storm is primarily associated with the thermospheric neutral composition change. Because the change of the LBHS intensity is minor, the increase of the atomic oxygen number density is responsible for the O/N₂ ratio increase in the northern low to middle latitudes.

3.2. 8 November 2004 Storm

[19] The severity of the storm on 8 November 2004 is comparable to that on 20 November 2003, and the disturbances in the ionosphere and thermosphere are similar in both storms.

Figure 5 is the same format as Figure 1 for the GUVI and CHAMP observations on the eighth (Figures 5b and 5c) and the sixth (Figures 5d and 5e) of November 2004. The observations on the sixth are taken as the reference for the quiet time. The LT of the GUVI and CHAMP observations is around 1300 LT. Three CHAMP orbits in Figure 5b are indicated by labels “1”, “2”, and “3” in Figures 6 and 7.

[20] The GUVI O/N₂ ratio map (Figure 5) shows that the O/N₂ values before the storm (Figure 5d) are dramatically reduced during the storm (Figure 5b). The area of the O/N₂

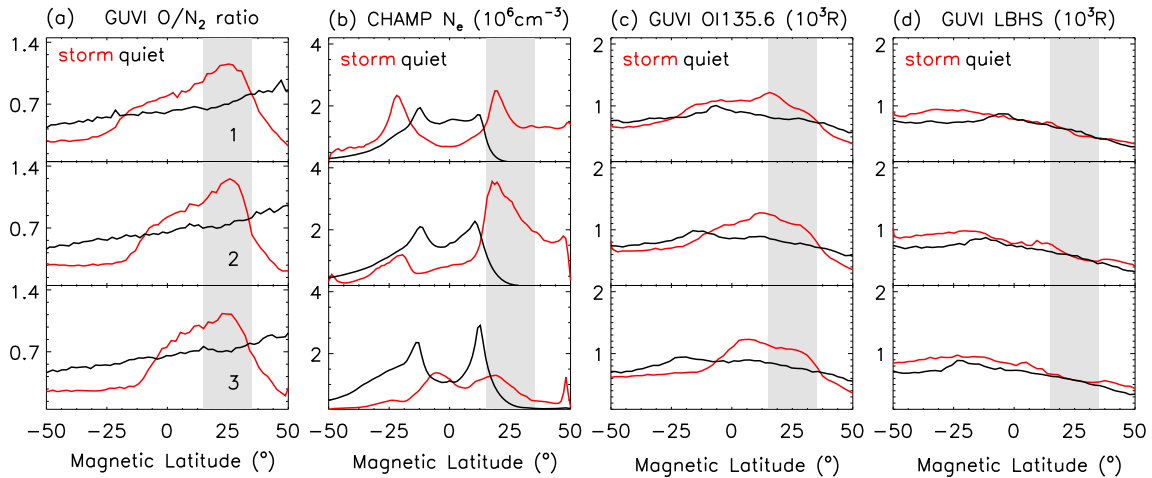


Figure 6. Comparison of the observations on 8 (red curves) and 6 (black curves) November 2004 along the CHAMP orbits shown in Figure 5b. (a) GUVI O/N₂ ratio. (b) CHAMP electron density. (c) GUVI OI 135.6 nm intensity. (d) GUVI LBHS intensity. For the details, refer to the Figure 2 caption.

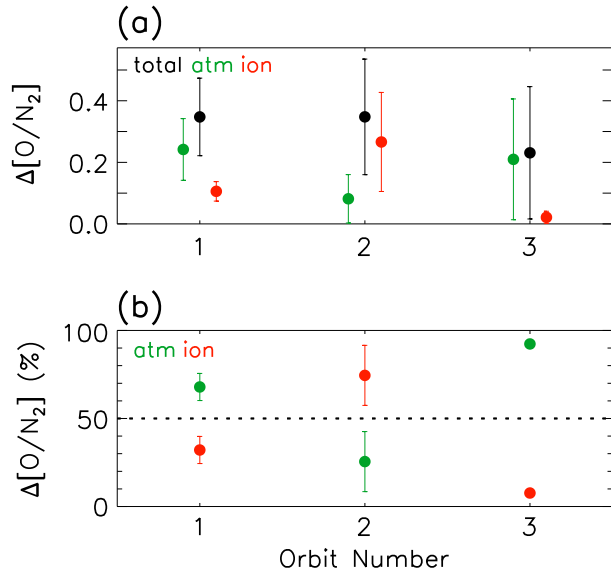


Figure 7. Comparison of the thermospheric and ionospheric contributions to the O/N₂ ratio increase during the 8 November 2004 storm. (a) The storm time increase of the O/N₂ ratio observed by GUVI (black dots) and caused by the increase of the OI 135.6 nm emission originating from the thermosphere (green dots), and ionosphere (red dots). (b) Percentage contributions of the OI 135.6 nm emissions originating from the thermosphere (green dots) and ionosphere (red dots) to the storm time O/N₂ ratio increase.

ratio enhancements can be divided into two regions. In the longitudes of 40°–110°E (Indian sector), the O/N₂ ratio during the storm is greater than that before the storm, but the electron density during the storm is smaller than that before the storm. Thus, the O/N₂ ratio increase in the Indian sector is attributed to the thermospheric neutral composition change. In the longitudes of 110°–180°E (East Asian sector) in the northern middle latitudes, both the O/N₂ ratio and electron density during the storm are greater than those before the storm. This region is the place where $I_{135.6}$ contributes to the increase in the O/N₂ ratio.

[21] Figure 6 presents the (a) GUVI O/N₂ ratio, (b) CHAMP electron density, (c) GUVI OI 135.6 nm intensity, and (d) GUVI LBHS intensity along the three CHAMP orbits shown in Figure 5b. The black and red curves are the observations on the sixth and eighth, respectively. The difference in the LBHS intensities between the 2 days is small in the latitude interval indicated by the gray shading. In that latitude region, the O/N₂ ratio, electron density, and OI 135.6 nm intensity are significantly increased during the storm. Therefore, the increase of OI 135.6 nm intensity is responsible for the O/N₂ ratio increase in that region. The altitude profiles of the OI 135.6 nm intensity derived from the GUVI limb scan data (not shown) are similar to those shown in Figure 3 and demonstrate the significant increase of the emission in the *F* region height during the storm.

[22] The average $[\Delta\text{O}/\text{N}_2]_T$, $[\Delta\text{O}/\text{N}_2]_A$, and $[\Delta\text{O}/\text{N}_2]_I$ are calculated using the method described in section 3.1. Those values for the three CHAMP orbits are shown in Figure 7a. Figure 7b shows the percentage contributions of $A_{135.6}$ and the $I_{135.6}$ disturbances to $[\Delta\text{O}/\text{N}_2]_T$. Along orbits 1 and 3, the contributions

of $A_{135.6}$ to $[\Delta\text{O}/\text{N}_2]_T$ are 68% and 93%, respectively. On orbit 2, however, the contribution of $I_{135.6}$ to $[\Delta\text{O}/\text{N}_2]_T$ is 76% and the ionospheric disturbance dominates the increase of the O/N₂ ratio. As we can see from Figure 6, the increase of plasma density along orbit 2 is much more significant than along orbits 1 and 3, although the increase in the GUVI OI 135.6 nm intensity is comparable along the three orbits.

4. Conclusions

[23] We have investigated the contribution of the OI 135.6 nm emission originating in the ionosphere (that is to say, the radiative recombination contribution) to the GUVI O/N₂ ratio by using the observations during the large geomagnetic storms on 20 November 2003 and 8 November 2004. The nadir-looking OI 135.6 nm emission originating from the ionosphere is calculated by using the USU-GAIM model ionosphere after scaling the predictions with the CHAMP electron density data. Our results show that the magnitude of the O/N₂ ratio increase in the regions where the plasma density enhancements are severe (in the northern low to middle latitudes during both storms) is significantly altered by the contribution of the OI 135.6 nm emission originating from the ionospheric radiative recombination. Although our calculation is a rough estimate of the ionospheric effect on the storm time O/N₂ ratio, overestimation of the thermospheric neutral composition disturbance by the GUVI O/N₂ ratio should not be ignored under these circumstances. This fact should be taken into account when GUVI O/N₂ ratio is used as a diagnostic of the thermospheric neutral composition change during severe geomagnetic storms.

[24] There are two additional important points that the reader should bear in mind and that we intend to address in future work. The first is that the O/N₂ ratio was originally intended as tool for scanning the vast amount of data obtained by GUVI in order to locate events that warranted further, more detailed study. Even 20 years ago, when the GUVI instrument was proposed, the assumption was that model data comparisons would be made on a “radiance-to-radiance basis.” Model predictions should be used to calculate the radiance as it would be observed by GUVI, if one wishes to make a detailed comparison of the model with phenomena. The second point that we are working to explore is that GUVI scans the disk and the limb. The limb scan provides altitude profiles of the radiance. These altitude profiles of the radiance should in principle enable one to retrieve the O⁺ contribution as well as the photoelectron excitation component of O.

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